Sediment Trapping Pathways and Mechanisms through the Mekong Tidal River and Subaqueous Delta

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LONG-TERM GOALS

A long-term goal of our sediment transport and deposition investigations is to link sediment-transport processes to the formation and preservation of event beds in sediment deposits. The general aim of this project is to investigate how forcing processes affect the sediment-transport dynamics that act to effect the delivery and retention of fine-grained sediment through tidal rivers and in shallow-water coastal regions. We strive to understand how the delicate balance of ebb and flood sediment fluxes is maintained to create tidal flat and mangrove complexes, and distributary shoals and islands within tidal rivers. All of these environments are characterized by variable bathymetry and variable seabed stability, and our goal is to answer the question: How do the processes that control the transfer of fine-grained sediment, e.g., tidal, riverine and other seasonal processes (e.g., winds/waves, precipitation, temperature and biological factors) influence the transport pathways, seabed erosion/deposition, and morphological development in shallow tidally influenced systems?

Understanding the transfer and transformation of sediment between terrestrial source and marine sink is essential for knowledge of global carbon budgets, landform evolution, and interpreting the stratigraphic record. Sediment is eroded, transported, and trapped via a myriad of processes along the continuum from terrestrial to oceanic environments. At present, we are focusing on sedimentary phenomena in relatively unstudied components within a source-to-sink framework: the connection between the tidal river and the subaqueous delta on the inner continental shelf, and sediment sinks within vegetated/mangrove shoreline complexes. Our overall hypothesis is that sediment-transport signals of flux magnitude, grain size, and dominant pathways are modulated within the tidal river and tidal floodplains before the delivery of sediment to the continental shelf, and thus processes in these regions exert a control on the ultimate fate of sediment particles.

OBJECTIVES

This research is designed to investigate sources and sinks of sediment in the tidal river and intertidal areas of the overall source-to-sink system. We report here on preliminary results from the Tropical Deltas DRI on the Mekong River, along with results from the Amazon River delta system that are guiding our efforts in the Mekong system.

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Our objectives focus on the following three areas:

1. **Transport Pathways in the Tidal River**. In many large rivers the tidal reach is largely unstudied, and the sedimentary dynamics within them control the magnitude and routing of particles onto the continental shelf. We hypothesize that there are mutually exclusive pathways for sediment on flood and ebb tides that control the deposition of sediment into distributary islands, impact the storage and release of sediment in both the main stem and floodplain areas, and alter the delivery mechanisms to the continental shelf, thereby placing controls on sediment fate.

2. **Sediment Retention and Release on Mangrove/Vegetated Intertidal Areas**. Along the main stem tidal river and coastal banks may be shorelines lined with vegetation (mangroves at the seaward fringe and other brackish-water vegetation in the fresher reaches). We seek to explore the role of the tidal channels in routing sediment to and from the tidal floodplains considering areas with vegetated shorelines, and to contrast these processes to those investigated in previous studies of unvegetated intertidal regions (Tidal Flats DRI; Nowacki & Ogston, 2013; Webster et al., 2013; Boldt et al., 2013).

3. **Understanding differences between natural (Amazon) and human-impacted (Mekong) large tropical deltas**. The tidal Mekong River has been highly impacted by humans, and the sub-aerial delta is the site of a large proportion of Vietnamese agricultural production. Our work on the tidal river and shoreline regions of another large tropical delta, the Amazon, allows comparison of connections between remotely sensed signatures, active sediment transport processes and depositional features that occur in a largely pristine capacity, with those in the human-impacted Mekong environments.

APPROACH

Our general approach is to use in situ observations to evaluate the hydrodynamics, sediment fluxes, and sediment characteristics within the coastal/fluvial environments listed above. Data from instrumented tripods and boat-mounted platforms deployed in the main stem of distributary river channels, in tidal channels of different size and on adjacent flat intertidal surfaces allow us to investigate the hydrodynamics and sediment dynamics of each morphological setting. We determine water and sediment fluxes and evaluate the importance of varying meteorological forcing on the sediment-transport dynamics. In addition, we strive to work with other investigators to enhance modeling and remote sensing efforts, and to develop an overall understanding of the system dynamics.

Transport Pathways in the Tidal River

We investigate water and sediment fluxes in the tidal river by surveying transects over complete 24-hour tidal cycles and deploying time-series instrumentation over the fortnightly cycle. During August 2012 a preliminary investigation was conducted in the lower tidal river (Song Hau distributary) of the Mekong River during high river discharge conditions, and in April 2013 a follow-on study was added to provide a contrasting data set under low river discharge conditions. These preliminary studies were undertaken in the region where the tidal river separates around Cu Lao Dung Island (Fig. 1). In these preliminary efforts, we undertook spatial surveys of the river distributary around the island (shown in Fig. 1) which allows us to create a preliminary bathymetric map of the channel studied (Fig. 2). We focused hydrodynamic and sediment transport studies on transects that encompassed the transition from fluvial to estuarine. The boat transited for 24 hours across the channels at these transects, in

order to delineate semi-diurnal variations in fluxes. We continuously operated an ADCP to measure current velocities, backscatter and bathymetry. We also profiled with CTD/OBS, and suspended-sediment samples were collected for calibration of the ADCP backscatter and OBS. These water samples also will be used to investigate suspended-sediment grain size and extent of flocculation.

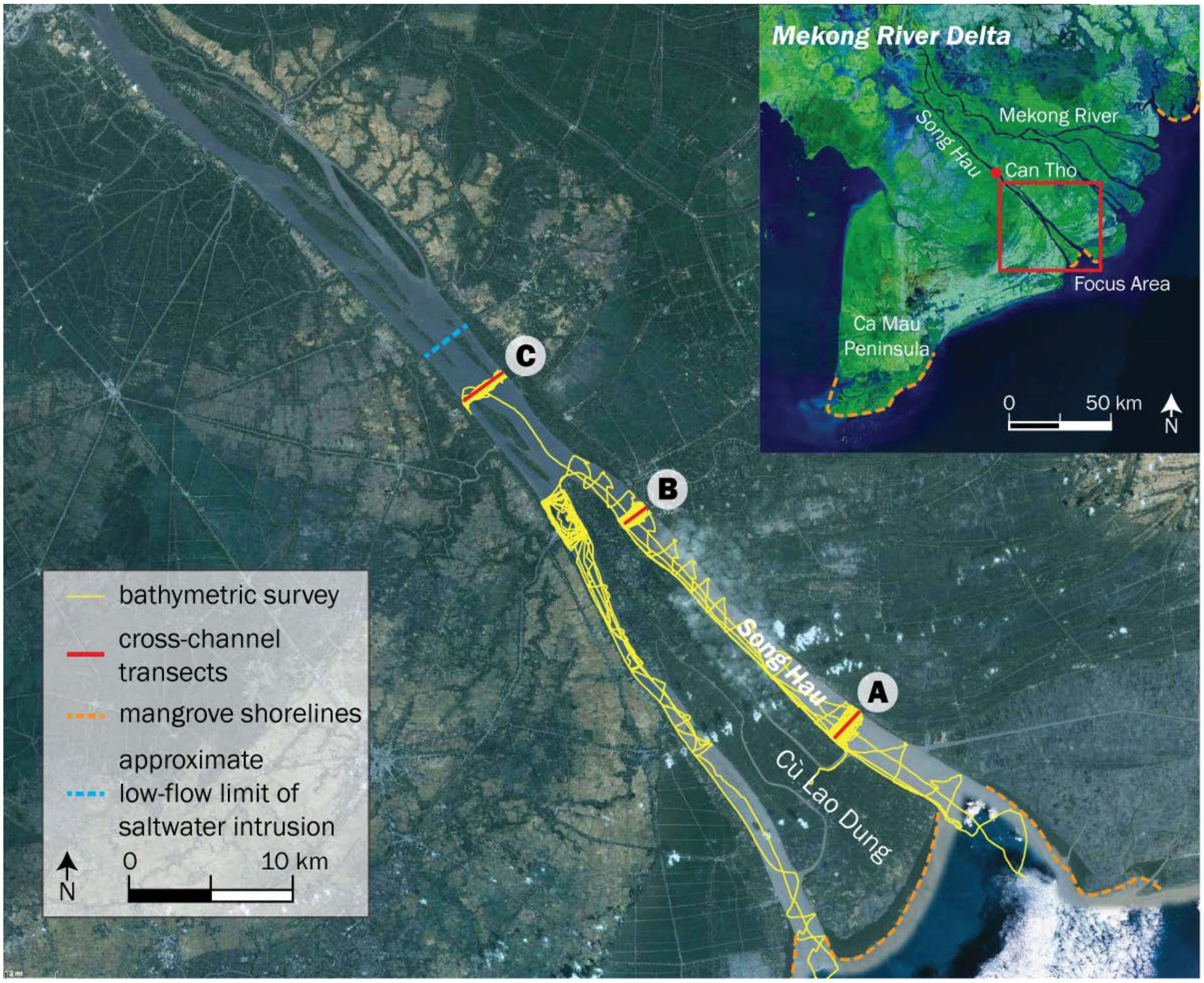

Figure 1. Tracklines of the spatial survey of bathymetry, currents, water-column structure, and suspended-sediment concentrations around Cu Lao Dung island in the Song Hau distributary of the Mekong River. Letters indicate locations of 25-hour ADCP surveys.

We are processing this data at present to address the evolution from tidal river dynamics to estuarine dynamics as it relates to the sediment transport and budget through the tidal river. During high-flow conditions, as was the case in August 2012, the upper transect (B) was predicted to be entirely freshwater, and the lower transect (A) was predicted to be at the edge of the estuarine processes (Wolanski et al., 1998; Mekong River Commission, 2005), and this was seen to be true, while during low-flow conditions the limit of salt penetration was significantly farther upriver (to C). The integrated suspended-sediment concentration and acoustic backscatter data sets provide information on the pathways and potential for remotely sensed signatures to interpret processes and bathymetry. We plan to combine our sediment-transport data sets with those of other investigators undertaking studies focused on bed sediment composition to understand the processes and resulting morphologies within the tidal main stem.

Sediment Retention and Release on Mangrove/Vegetated Intertidal Areas
In the initial preliminary August 2012 experiment focused on the distributaries surrounding Cu Lao Dung Island, we scoured the lower tidal river for natural channels that would lead into interior tidal floodplain areas, but were unsuccessful due to the diking of the former tidal floodplains for agriculture. In the April 2013 experiment we investigated the mangrove fringe on seaward side of the island and found a thriving, natural mangrove forest. We are planning a "mini-mangrove" experiment in February 2014 to investigate the feasibility of doing experimental work in this mangrove fringe.

Subsequently, in the larger focused experiments (tentatively scheduled in September 2014 and February 2015), instruments (e.g., Aquadopp high-resolution current profiler, wave gauges and OBS) will be deployed on the bed near the entrance of vegetated tidal channels or furrows located within the seaward mangrove fringe of Cu Lao Dung island, and maintained throughout the neap to spring transition. This is an approach that has been proven in studies of Willapa Bay (Nowacki and Ogston, 2013) and Amazon tidal channels (Nowacki et al., 2012). Our focus with these studies will be on fluid and sediment exchange between the offshore shoals and the mangrove forest. As there are very few natural channels that incise the Mekong tidal floodplain, we plan to use the contrasting Amazon tidal river to further investigate the role in sediment storage of these types of intertidal areas. Preliminary work has revealed that these channels ultimately meld into the tidal floodplain and may serve as effective conduits for importing or exporting sediment. We will investigate questions that include: What are the processes by which tidal floodplain channels serve to import or export sediment over hourly to weekly time scales?

Comparison with another large tropical delta system, the Amazon Delta
We plan to compare flow dynamics and sedimentary processes within the lower Mekong River with those in the Amazon River. Both systems are vast and it is recognized that only specific sections or processes can be addressed in each system. The near-continuous levee structures along the shorelines of the Mekong River create a system without porous boundaries, and therefore we can isolate main stem channel processes better, while in the Amazon River with little human impact, we can address the natural interactions between the channels and tidal floodplains, and how the relationship with the tidal floodplain impacts sedimentary dynamics in the main stem of the river.

WORK COMPLETED

The primary field focus of this year was a second data-collection effort on the tidal Mekong River, Vietnam, to follow up on preliminary work completed in 2012. Much of our effort on the Tropical Deltas DRI has been in developing relationships with Vietnamese colleagues and traversing the path

through their political, cultural, and scientific systems to allow us to undertake our joint field effort. The initial field campaign was conducted in August-September 2012, which corresponded to high seasonal discharge on the Mekong River. A follow-up field campaign was carried out 20-28 April, 2013 during low discharge.

Data collected during the initial survey in August 2012 included spatial surveys of the Song Hau distributary of the Mekong near Cu Lao Dung island (Fig. 1), 25-hour ADCP transects at two locations along the Song Hau, and focused data collection around small deltaic islands within the channel. The 2013 data-collection effort was focused on repeat surveys of the ADCP transect locations occupied in 2012 and the addition of a third, farther upstream location. The three locations were chosen for their relevance to oceanic salinity presence or absence at different stages in the seasonal discharge hydrograph. The downstream location experiences salt-water intrusion during certain periods of the tide at high discharge, and salinity is always present during low discharge. The middle transect is completely fresh (but with reversing flow) during high discharge, and has salinity only occasionally present during low discharge. The upstream transect has minimal salinity (< 3 PSU) throughout the tidal cycle during low discharge. Pressure, temperature and salinity moorings were deployed concurrently with the ADCP surveys. These complementary data sets provide intriguing preliminary data for the Tropical Deltas DRI, and their successful completion is proof of our improved understanding of the pathways and procedures necessary to undertake scientific research in this region.

RESULTS

From our preliminary studies in the mainstem of the Mekong river, we have learned much about the best ways to conduct research with our Vietnamese collaborators and within the Mekong River system, and will use these results to guide subsequent work under this project and assist other PIs in their program development.

Bathymetry of the tidal river channel
The Song Hau distributary channel of the Mekong River appears from the surface to be quite regular and simple in form. From our transits of the channel and spatial surveys, we can start to build more detailed bathymetry that shows the complexity of the river within the region spanning the transition from estuarine to freshwater tidal river. Near the mouth (in the region of estuarine processes much of the year), the river displays a typical form with a mouth shoal surrounded by two deeper incised channels (Fig. 2). But farther upstream where the river transitions to tidal river during low flow conditions, the channel is asymmetrical with the deepest channel residing on the east/west side of the river.

Tidally averaged flow dynamics
Hydrodynamic data from the preliminary set of low-flow/high-flow cruises is in the process of being analyzed. We see a clear distinction in the flows along and across the tidal river transects both spatiall and seasonally (Fig. 3). During high flow (August 2012) near the mouth of the river (Transect A), tidally varying discharge ranged from +20600 to -14400 m^3/s (ebb positive). At low flow (April 2013), tidally varying discharge ranged from +20100 to -23100 m^3/s.

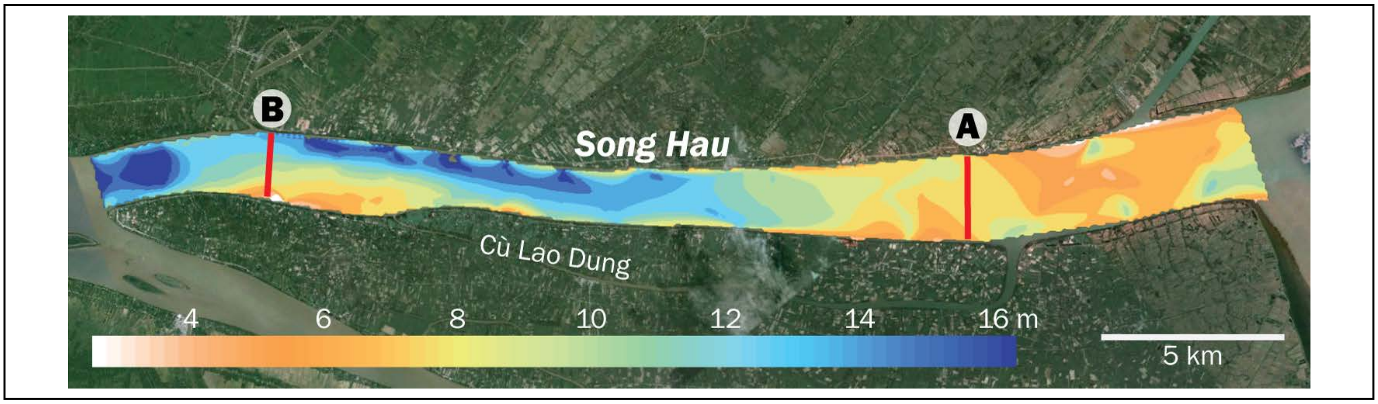

Figure 2. Contoured bathymetric map of the left channel of the Song Hau as determined from single-beam echosounder survey. Trackline density is indicated in Figure 1.

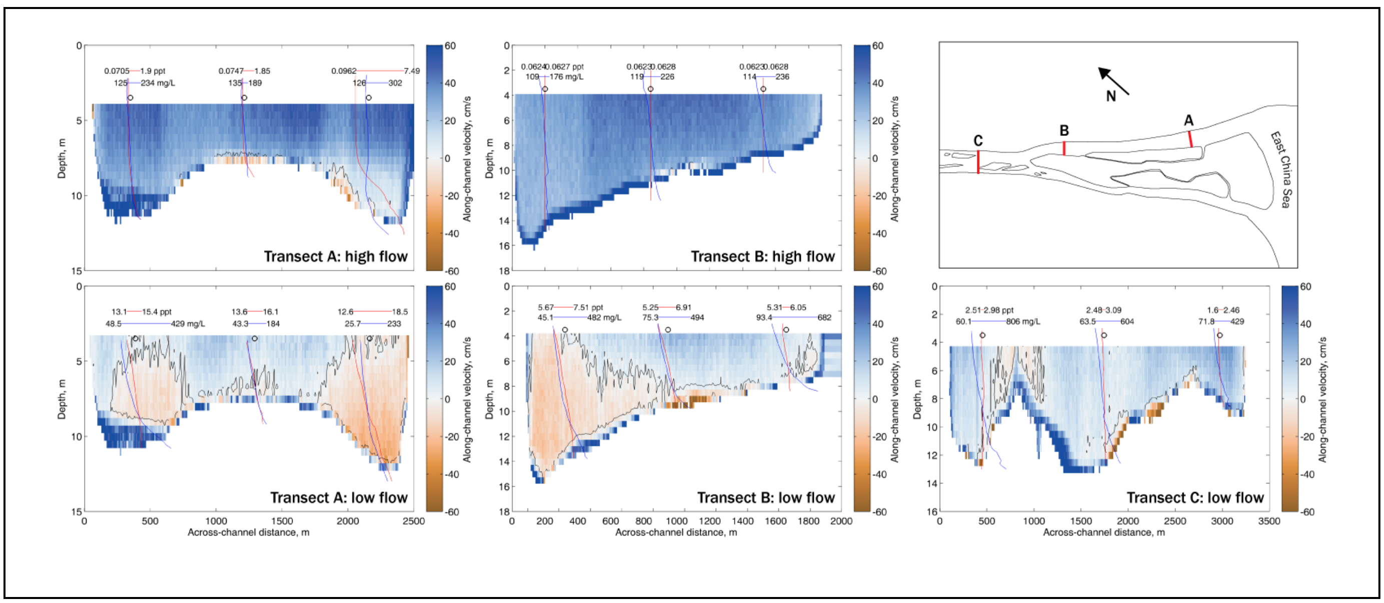

Figure 3. Tidally averaged along-channel flows at three cross-sections within the Song Hau distributary of the Mekong River, during high (top) and low discharge (bottom). Note upstream flow at A and B during low discharge, likely due to baroclinic effects.

The tidally averaged flow through the cross sections sampled during the two research cruises, exhibit vast variations in the flow dynamics between the different river discharge regimes. During high flow, although flow reverses through the tidal cycle in both the transects measured, net downstream flow is most evident throughout the cross section, except near the seabed at the mouth location (A). Net upstream flow is preferentially located in the east side of the river channel, and at the B transect ~15 km upstream no areas of net upstream flow were observed and the flow focus was centered in the trapezoidal channel. In contrast, under low flow conditions, net upstream flow is observed within the two side channels near the mouth, focused on the western side. At the B transect, flow on the deepest

side of the channel is net upstream, indicating a meandering flow and sediment pathway driven by cross-channel estuarine flows and merging of the two side channel paths into one.

Tidally influenced suspended-sediment concentrations

Suspended-sediment concentrations in the most riverine transect ranged from100-180 mg/L in the surface waters during high river discharge, and 40-70 mg/L during low river discharge. Near the mouth, and where salinities reached up to 7 ppt at the maximum extent of salt intrusion, the suspended-sediment concentrations depended on tidal stage, and could be significantly higher (> 1 g/L) consistent with the active estuarine processes in that zone. During low discharge, the vertical gradient in suspended-sediment concentrations was significantly stronger than at higher discharge, resulting in greater nearbed concentrations during low discharge than during high discharge.

The suspended-sediment concentrations observed in the Mekong system are generally similar to those in the Amazon tidal river in their range and tidal variability, although annual Amazon discharge is about 11 times greater than the Mekong. Surface suspended-sediment conentrations in the Amazon River near the mouth (but far from the zone of estuarine processes) typically range from 30 to 40 mg/L at low discharge stages, and 50 to 70 mg/L at higher flows.

Sediment transport in small intertidal channels

As indicated in the approach section, we have not yet deployed instrumentation in small intertidal channels in either the tidal river or the mangrove fringe on the Mekong River. We have identified areas for upcoming deployments planned for February 2014. To undertake this work we are using techniques and results gained from the Amazon River intertidal channel deployments to guide our efforts. We plan to deploy current meters, wave sensors, and optical sensors for suspended-sediment concentration in an array extending from shallow coastal depths, crossing through the line of mangrove growth, and into the mangrove forest to look at the import and export of suspended sediment from the mangrove forest and the role of wave attenuation in those processes.

As an example of the processes that occur in channels that disect mangrove forests, data from the Bragança region near the mouth of the Amazon River is shown in Figure 4. Results from preliminary investigations in several tidal channels along the Amazon tidal river show some intriguing processes at work that are relevant to sediment transport to the tidal floodplain, for example thermal fronts appear to be a significant factor in importing sediment upstream, and a turbidity maximum resulting from flow convergence is an important part of this process.

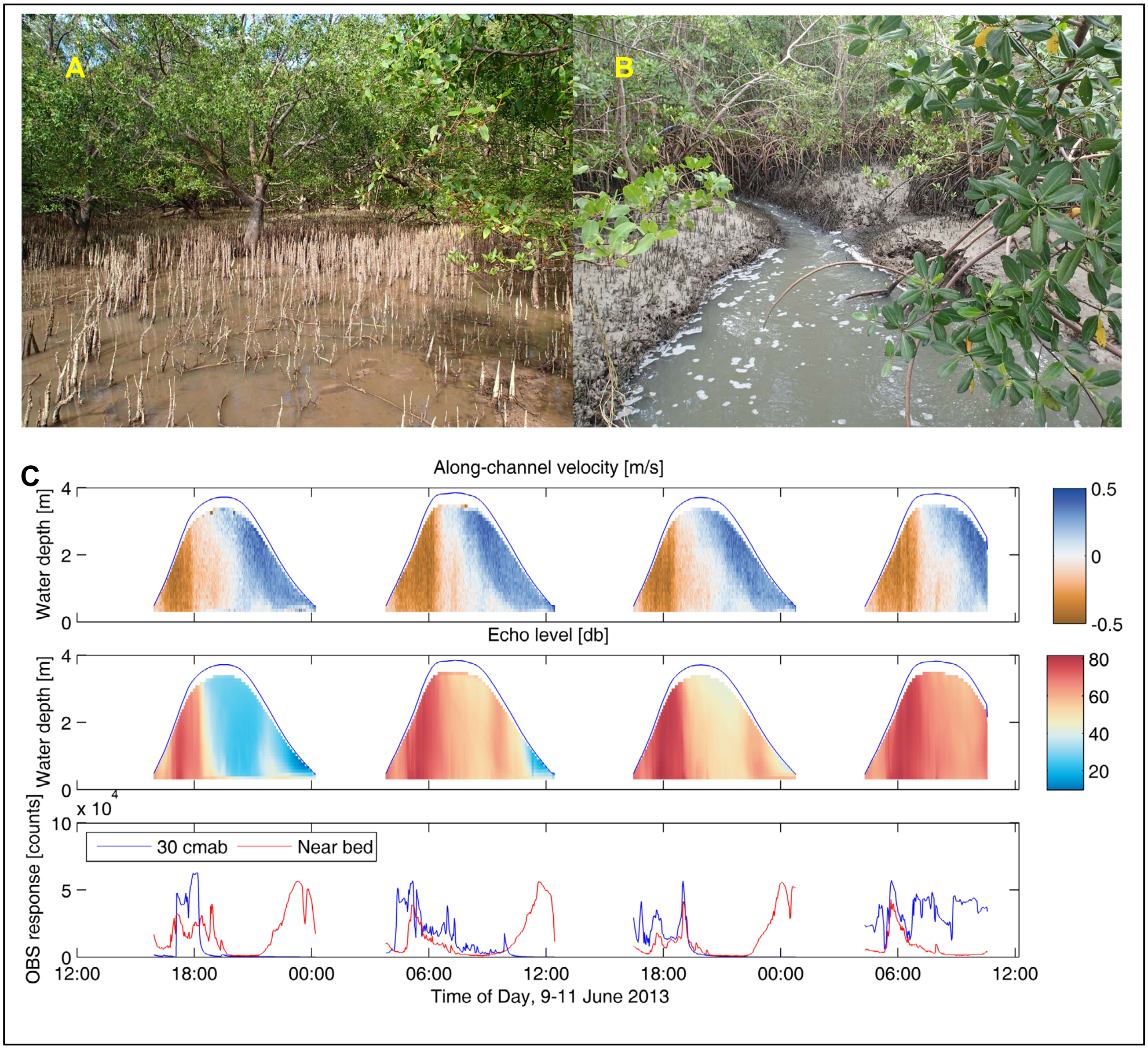

Figure 4. Photos of mangrove environments a) on the seaward fringe of Cu Lao Dung Island in the Mekong Delta, and b) in the Bragança region of the Amazon Delta. c) An example of time-series data collected in a tidal channel near the region of the photo b, illustrating the complex ebb and flood tidal fluxes through this channel.

IMPACT/APPLICATIONS

Rivers are the largest suppliers of particulate material to the world ocean (Milliman and Meade, 1983), and the pathways that sediment takes in the transition from riverine to marine and the resulting water-surface expression can provide information about the bathymetry, shoreline processes, and ultimate fate of these particles. For the major rivers of the world, the gateways to the open ocean include the freshwater tidal reach, which can extend for hundreds of kilometers, and brackish to marine intertidal areas. The hydrodynamic and sedimentary processes in these environments remain poorly understood.

Of particular interest are areas that temporarily store and release sediment such as tidal floodplains and the channels that incise them, deltaic distributaries and islands, and vegetated and unvegetated tidal areas. Understanding the processes in these environments, their impacts on mass budgets, and the most appropriate means to model and interpret remotely sensed observations of them requires research that is underway at present. Controls through the tidal river and tidal-flat gateways influence the signal propagation of sediment discharge from river to shelf environments. Where deltaic deposits are formed on the continental shelf, these controls should be detectable in the pathways and signatures of sediment flux and deposition.

The morphology and seabed properties of tidal flats and channels, tidal floodplains, and tidal rivers are linked to the mechanisms and rates of transport and deposition on the vegetated and/or unvegetated flats and in the channels that bisect them, and our studies aim to enhance the ability to predict these properties in other unstudied areas. Our studies also provide insight for coastal management that can be transferred to other tidal environments, allowing evaluation of the impacts of humans and invasive species on sediment dynamics.

As part of this program, we intend to enhance capacities in the field of coastal and marine geology, and, in particular, estuarine and coastal sedimentary dynamics in Vietnam. We have incorporated training activities during our field work. All of our field activities have and will have both US and Vietnamese student participation and we are training these students on the principles, operation, and data analysis techniques for each of the instruments we use in the field. Young Vietnamese scientists have participated in the preliminary field efforts, and two Vietnamese scientists were hosted at the University of Washington for a month in 2013 to learn advanced techniques that can be implemented in Vietnam.

RELATED PROJECTS

We have had a parallel program studying tidal river and vegetated shorelines in the Amazon River dispersal system, partially funded by NSF International Programs. The focus of this work is to develop a network of international collaborators and has included preliminary data collection efforts. The macro- to meso- tidal Amazon system provides a contrasting large tropical deltaic environment that has had little anthropogenic modification, while the mesotidal Mekong system has been intensely manipulated by mankind. Comparison of processes across these two study areas allow us to discuss the effects of anthropogenic impacts.

In addition, we participated in a short course (PASI: Toward a Sustained Operational River-to-Shelf Observation and Prediction System for the Amazon), which was supported by DOE, NSF, and ONR. This program was intended to inform participants about the sedimentary processes in the Amazon fluvial-coast-shelf region and to foster working relationships between the US and Brazilian scientists. PI Ogston lectured in the PASI program and helped organize and guide the field trip that demonstrated the use of tools and instruments in coastal mangrove and nearshore to shelf environments.

We are striving to foster similar working relationships and opportunities with colleagues in Vietnam. An essential goal of the project in the Mekong delta is capacity building in the field of coastal and marine geology, and, in particular, estuarine and coastal sedimentary dynamics in Vietnam. The work we are undertaking will be adapted as other Vietnamese and US investigators become involved in the program. Particularly, we will adjust our efforts to accommodate needs of remote sensing studies and numerical modeling efforts.

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